FUEL CELLS FOR ENERGY PRODUCTION

By

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Abstract

The goal of the project was to replace the energy the University of Arizona currently purchases from Tucson Electric Power (TEP) with cheaper, cleaner power from a solid oxide fuel cell (SOFC). Natural gas is fed through a desulfurizer to remove sulfur and is then fed into a steam methane reformer where methane reacts with steam to produce hydrogen and carbon dioxide, which is then fed to the fuel cell. In the fuel cell, hydrogen and methane are reacted with oxygen from the air, which produces water and some carbon dioxide. The waste stream from the fuel cell containing steam, carbon dioxide, and unreacted compounds is fed to an Organic Rankine Cycle (ORC) which generates more energy by removing heat from the waste stream. Water is condensed out through the ORC and the gaseous stream is scrubbed of carbon dioxide before being released to the atmosphere. This plant is not economically feasible due to the high capital cost as well as the yearly operating costs exceeding what the university currently pays for the same amount of electricity.

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1. Introduction

1.1 Overall Goal

The objective of this project is to feasibly replace the energy the University of Arizona currently purchases from Tucson Electric Power (TEP) with energy produced using solid oxide fuel cells with natural gas as a feedstock.

1.2 Current Market Information

For the 2017 Fiscal Year, the University of Arizona consumed a total of 250,000 MWh of energy. The university generates about 98,000 MWh through two on-campus natural gas fired turbines and on-campus photovoltaic arrays. The university purchased 152,000 MWh of electricity from TEP for $12.9 million. The per unit cost of the energy the university purchased from TEP is $0.085/kWh. These factors are important for consideration in achieving the project goal of replacing the purchased TEP energy with fuel cell energy.

Fuel cells are a technology that is receiving more research and growing in popularity in the energy sector. Advantages for fuel cells are that they are a cleaner than combustion-based energy sources and fuel cells with a pure hydrogen feed have zero carbon dioxide emissions. They can also operate at higher efficiencies than combustion energy and have many different applications. The research that is necessary for fuel cells is increasing performance, lifetime, and lowering costs. Fuel cell membranes are very expensive and PEM fuel cell catalysts make them economically inefficient in certain processes. Increasing the performance is an important factor to combat cost so more energy is produced. Lifetime analysis is important for cost reduction so replacing the stacks is not as frequent. These hurdles are what companies like Fuel Cell Energy are trying to overcome to make fuel cells a better form of energy (Fuel Cells).

Fuel cell applications are wide and they can be portable, stationary or used for transportation (FuelCellToday). Fuel cells were even used in the Apollo space missions to the moon to provide energy for the spacecraft and produce clean drinking water for the astronauts. They were advantageous because they are compact, efficient, and use hydrogen as a feedstock. Now fuel cells can be used in large scale energy production, which is advantageous due to the use of natural gas or hydrogen and the low emissions. For that reason, some colleges have started to use fuel cell energy to power their campuses. California State University San Marcos, University of Connecticut, and Rochester Institute of technology are all colleges that use fuel cell energy to power their schools. Other schools have explored switching to fuel cell power and that is the goal of this project (Colleges).

Currently about one third of U.S. energy production comes from natural gas in the form of gas and steam turbines (Electricity). As this is a large portion of the energy production, making it cleaner and more affordable is desirable. Fuel cells have potential to make natural gas energy cleaner if the technology progresses in becoming cheaper and more durable.

1.3 Project Premises and Assumptions

The steam methane reformer is assumed to only have one forward reaction taking place in the reformer that consumes one mole of methane, two moles of steam to produce four moles of hydrogen.

In the calculations, it is assumed that all of the sulfur is removed from the natural gas stream in the desulfurization column. The ORC system is assumed to operate at the efficiency and rate that Access Energy states. They also state that the system needs little to no maintenance and replacement which is assumed to have no cost in the design of the plant. The fan and preheater are assumed to have the consistent conditions of Tucson weather. Additionally, based on the weather conditions the fan is assumed to run year round.

There were three major assumptions made in calculations for the fuel cells. The first assumption was that the fuel cell would operate best a one atmosphere of pressure. This also eliminated any dangerous operating pressures. The second assumption made was that the parameters in Kabza's formulary applied to this fuel cell project. Along those lines, a similar assumption was made using Al-Hamamre's reaction kinetics that was assumed to work for this project as well.

For every annual calculation, there was an assumption of 24 hours for 365 days of operation.

2. Process Description, Rationale and Optimization

2.1 Block Flow Diagram

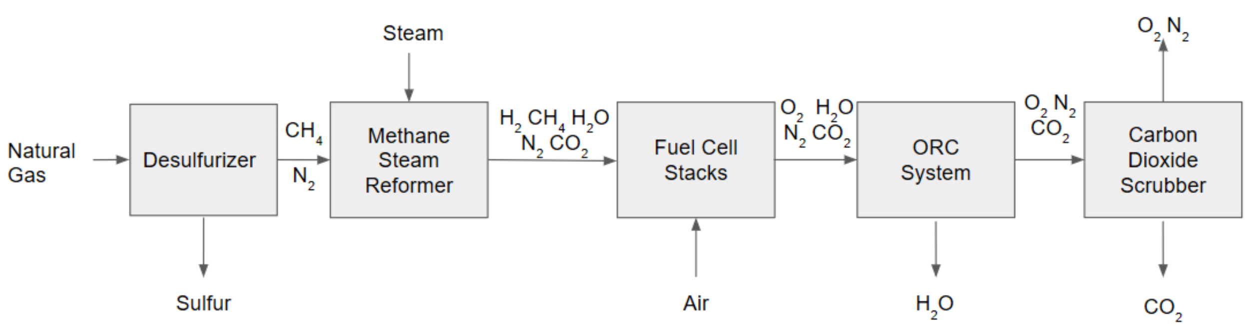

Figure 1: Block Flow Diagram

2.2 Process Flow Diagram

T – 101	R – 101	F – 101A/B	H – 101	FC – 101-5094	TE – 101-5094	HR – 101-2	V-101	P-101 A/B	T-102-103
Desulfurizer Adsorption Column	Refomer	Fan	Preheater	Fuel Cell Stack	Electric Thermal Element	Organic Rankine Cycle	MEA Storage Tank	MEA Pump	Carbon Dioxide Scrubber

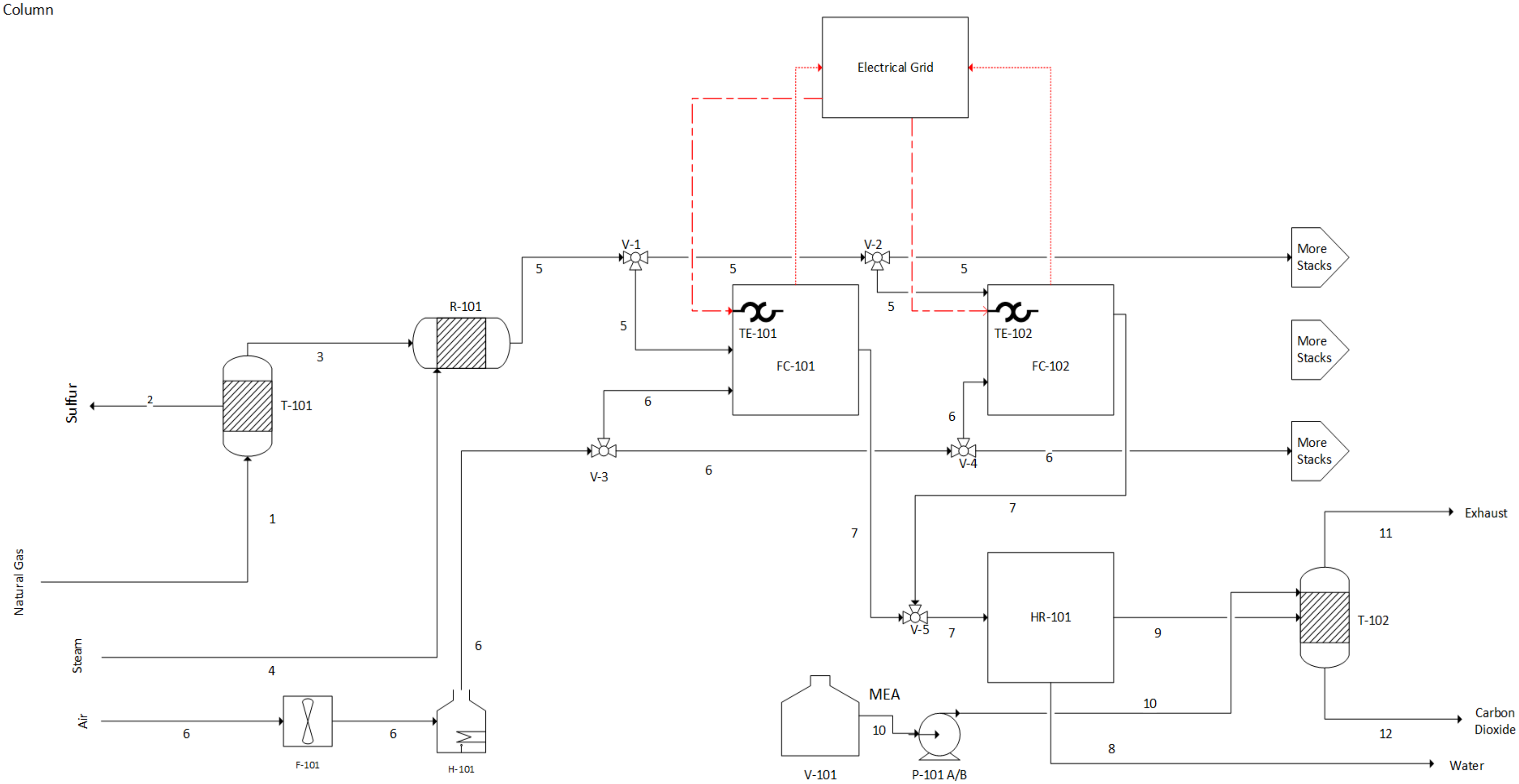

Figure 2: Process Flow Diagram

2.3 Equipment Table

Table I. Equipment specifications in the process

Equipment				
Vessels/ Towers/ Reactors	T101 A/B (Desulfurizer)	R-102 (Reformer)	T102-103 (Carbon Dioxide Scrubber)	V-101 (Absorbent Storage tank)
Temperature (°C)	Ambient	700	40	Ambient
Pressure (atm)	1 atm	2.96	1 atm	1 atm
Orientation	Horizontal	Horizontal	Vertical	Vertical
MOC	Stainless steel	HK 40 Stainless Steel	Stainless Steel	Carbon Steel
Size				
Height/length	1.5 m	1 m	5 m	14 m
Diameter	0.3 m	2.11 m	3.5 m	9 m
Internals	CuY adsorbent	Tubular reactors with Nickel-Alumina catalyst coated fans, surrounded by furnace	Monoethanolamine (MEA) absorbent, 3 in ceramic Raschig rings for packing	Stores one half day supply of MEA
Fans	F101A/B			
Flow rate (kg/hr)	427913			
Fluid Density (kg/m^3)	1.225			
Power (kW)	92			

Solid Oxide Fuel Cells	FC101-2038			
Current Density (A/cm^2)	0.25			
Cell Area (cm^2)	437			
Cell Thickness (cm)	0.187			
Number of cells per stack	150			
Height of stack (cm)	28			
Volume of stack (cm^3)	12236			
Power per stack (kW)	9.64			
Total Number of Stacks	2038			
System Efficiency (%)	60			
Max Cell Voltage (V)	1.19			
Effective Cell Voltage (V)	0.98			
Heat Recovery System (Organic Rankine Cycle)	HR-101-2			

Number of systems	2			
Gross Power per system (kW)	115			
Flow rate (water) (kg/hr)	19693			
Preheater (air)	H-101			
Heat Power (kW)	87			
Flow rate (air) (kg/hr)	427914			
Electric Thermal Heating Element	TE 101-2038			
Time to Steady State Temp. for Catalyst (minutes)	3			
Power Needed per Stack (kW)	4.5			
Energy Needed per Stack per Startup (kWh)	0.225			
Total Energy Needed for Start-Up of Fuel Cells (MWh/yr)	0.917			
Steady State Temperature (K)	973			
Pumps	P-101 A/B			

Flow (kg/hr)	68500 kg/hr			
Fluid Density (kg/m^3)	1010 kg/m3			
Shaft Power (kW)	1.1 kW			

2.4 Stream Table

Table II. Flow rates and stream numbers for the process

Stream Number	1	2	3	4	5	6
Temperature (C)	25	75	75	110	700	700
Pressure (atm)	1	1	1	3	2.96	1
Vapor Fraction						
Mass Flow (kg/hr)	4509	0	4509	9847	14361	427914
Mole Flow (mol/hr)	277715	0	277715	546453	1135645	14832286
Component Flow (mol/hr)						
Hydrogen	0	0	0	0	622956	0
Methane	273226	0	273226	0	117487	0
Oxygen	0	0	0	0	0	3114780
Water	0	0	0	546453	234975	0
Carbon Dioxide	0	0	0	0	155739	0
Nitrogen	4488	0	4488	0	4488	11717506
Hydrogen Disulfide	0	0	0	0	0	0
MEA	0	0	0	0	0	0
Stream Number	7	8	9	10	11	12
Temperature (C)	700	40	40	40	40	40
Pressure (atm)	1	1	1	1	1	1
Vapor Fraction		0		0		
Mass Flow (kg/hr)	442272	19693	422579	68414	410915	80078
Mole Flow (mol/hr)	15656454	1092905	14563548	1120071	14298519	1385101
Component Flow (mol/hr)						
Hydrogen	0	0	0	0	0	0
Methane	0	0	0	0	0	0
Oxygen	2568327	0	2568327	0	2568327	0
Water	1092905	1092905	0	0	0	0
Carbon Dioxide	273226	0	273226	0	8197	265030
Nitrogen	11721994	0	11721994	0	11721994	0
Hydrogen Disulfide	0	0	0	0	0	0
MEA	0	0	0	1120071	0	1120071

2.5 Utility Table

Table III. Utility usage per year

Utility	Amount	Cost per Unit	Total Cost
Natural Gas	556,000 m3/yr	$0.262/m3	$146,000/yr
Steam	86,200,000 kg/yr	$0.0132/kg	$1,140,000/yr
Cooling Water	17,500 m3/yr	$0.03/m3	$526/yr
Electricity	1,580 MWh/yr	$85/MWh	$134,000/yr

2.6 Written Description of Process

The process for producing energy using solid fuel cells and a natural gas feed requires some preprocessing steps to convert the natural gas to a form suitable to feed to the fuel cells. The products of the electrochemical reaction that takes place within the fuel cells are also processed further to generate additional energy and to remove pollutants from the products that are released to the atmosphere.

The process flow diagram seen in figure 2 shows each step of the process for energy production with fuel cells. Pressurized natural gas from a supplier flows through a pipeline (stream 1) and is fed into an adsorption column (T-101) that contains CuY zeolites. The adsorption step removes all of the sulfur from the natural gas. The outlet stream from the adsorption column (stream 3) is fed into a steam methane reformer (R-102) where it reacts with steam (stream 4) to produce H_2 and CO_2.

The product stream from the reformer (stream 5), which contains H_2, CO_2, H_2O, N_2, and CH_4, and preheated air (stream 6) are fed to the solid oxide fuel cell stacks (FC-101-5094), in which an electrochemical reaction occurs, converting H_2 and O_2 to H_2O and generating electricity. The operating conditions of the fuel cells are atmospheric pressure and a temperature of 700°C. The outlet stream from the fuel cells (stream 7), which is composed of

O_2, CO_2, H_2O, and N_2 at a temperature of 700°C feeds into an Organic Rankine Cycle (HR-101-2) which recovers waste heat, cooling the stream down to approximately 40°C.

Due to the temperature change of the process stream through the ORC, the water condenses and separates from the other compounds still in the vapor phase. Water (stream 8) is one of the process outputs. The other components still in a vapor phase (stream 9) are fed to a carbon dioxide scrubber, an absorption column (T-102) where CO_2 is removed using a liquid absorbent, monoethanolamine (MEA). The CO_2 is absorbed into the MEA and separated from the O_2 and N_2 (stream 12). The gaseous O_2 and N_2 (stream 11) is released into the atmosphere. Stream 11 also contains a small fraction of CO_2 that is not removed in the scrubber.

2.7 Rationale for Process Choice

There are two main types of fuel cells. The first is a PEMFC, or a proton exchange membrane fuel cell. This fuel cell utilizes the reaction of hydrogen and oxygen to form water. One of the main issues with this method is the source of the hydrogen. Hydrogen is extremely flammable and is not readily available for large scale power production. PEMFC's thrive in small scale usage such as for cars and portable devices. PEMFC's operate at a lower temperature, from 80-200 degrees Celsius. One of the main reasons that PEMFC's are sought out as a future energy producer is due to their very eco-friendly waste product. Water is the only product from the reaction and is chemically pure after the reaction. Another downside to PEMFC's is the very finicky nature of the catalyst. The catalyst must remain at very stable temperatures and pressures and forces a slow start-up. Additionally, the catalyst is very sensitive to fuel types and will degrade quickly in the presence of hydrocarbons.

The second common type of fuel cell is an SOFC or solid oxide fuel cell. This type of fuel cell utilizes a reaction between a hydrocarbon and oxygen to form water and carbon dioxide. One of the downsides of the SOFC is its high operating temperatures of 700 degrees Celsius and above. This makes small scale and mobile applications very challenging. However, these high temperatures create more efficient power generators. Unfortunately, this type of fuel cell generates carbon dioxide as well as water for its waste products. The sulfur that is typically present in natural gas and other fuels is removed in the desulfurizer to avoid contamination and degradation of the fuel cell. The sulfur poisons the cathode and the anode and forces system downtime which reduces the amount of power produced.

For this process, a SOFC system is used with a reformer and a desulfurizer added on. The reformer increases the lifespan of the cathode and anode. This design is for long term energy production and can manage the high temperatures required by SOFC's. The reformer takes the desulfurized natural gas feed and reforms it into mostly hydrogen. This step was integrated in the process to maximize efficiency, reduce degradation of the fuel cells, and reduce the global footprint.

The thermal energy is captured through the organic rankine cycle system. The high temperature exhaust carbon dioxide, water, and nitrogen is utilized spin a turbine and generate additional electricity. This additional energy produced is then utilized by the carbon dioxide scrubber. At the end of the process, the scrubber eliminates close to 97% of the carbon dioxide emissions. This addition was made to ensure that the process remains a source of clean energy with a reduction in environmental impact when compared to traditional power plants.

3. Equipment Description, Rationale and Optimization

All equipment calculations are found in Appendix A.

T-101 Desulfurizer Adsorption Column

Natural gas is odorized by suppliers through the addition of sulfur compounds. However, sulfur is poisonous to the fuel cell catalysts and causes rapid degradation, so sulfur must be removed from natural gas prior to the fuel being fed to the fuel cells. The desulfurization adsorption column uses CuY zeolite adsorbents to selectively remove sulfur compounds from the natural gas feed. The CuY zeolites were chosen because they have a relatively high sulfur capacity compared to other adsorbents that could be used for this process (Yang). The operating conditions of the desulfurization column are ambient temperature and pressure (Yang). The equipment is designed to allow for complete removal of sulfur from the natural gas. One limitation of using the CuY zeolite adsorbent is that water competitively adsorbs, so in the presence of any moisture, the sulfur capacity of the adsorbent decreases, reducing its effectiveness. Thus, the desulfurization column is carefully controlled to prevent excess moisture from coming in contact with the adsorbents.

R-101 Reformer

The steam methane reformer for this process is used to convert methane from the natural gas into hydrogen which is a better fuel source for the fuel cell as pure hydrogen does not degrade the fuel cell. The reformer works by reacting methane and steam at 700 degrees Celsius and a pressure of 2.96 atm in the presence of a nickel catalyst fan to produce hydrogen and carbon dioxide (Xu). The conditions in the reformer are set so that one reaction happens in the reformer resulting in four moles of hydrogen produced for every one mole of methane feed into the reformer. Based on industrial conversion rates, 67% of reactants feed into the reformer are reacted (Xu). The products and unreacted compounds are then fed to the fuel cell. The reformer is 1 meter long and 2.11 meters high to allow for the nickel-plated fan. As the reaction that happens in the reformer is exothermic a stream of cooling water is used to keep the reformer at 700 degrees Celsius. The cooling water is supplied by the University's water system and drained into the University's waste water system so no additional pumps or infrastructure are required to cool the reformer.

F-101 A/B Fan

The fan for this process is to move outside air into the fuel cell stacks. The oxygen in the air is used to react with hydrogen to produce energy. The fan was sized to move 300 cubic feet per minutes which makes the fans power consumption to be 124 horsepower. The fan is run year-round all day so there is a backup fan that is used in case of maintenance or failure. The fan was chosen over a blower because it was more efficient for the process and fits the large scale need of air for the fuel cell stacks. The fan is made of stainless steel for durability because of the operating times (Seider).

H-101 Preheater

The preheater is necessary to heat the air produced by the fan to the operating temperature of 700 degrees Celsius. The preheater was sized using the heat duty needed for heating the ambient air (Seider). The heater runs on natural gas and is made out of stainless steel for longevity. The cost of the heater is roughly $17,000 for a 300,000 BTU/hr heat duty. 300,000 BTU/hr is necessary to heat the air to the right condition of 700 degrees Celsius so the fuel cell operates at the most efficient temperature. Without the preheater the fuel cell stacks won't run at optimal efficiency which reduces energy production.

FC-101-5094 Fuel Cell Stacks

The fuel cells were modeled after Elcogen's E3000 stacks. The CEO of Elcogen, Paul Hallanoro, shared specifications that are applicable to this specific system, which were used to develop a realistic model for this system. The information included details about the size, cost, efficiency, and current density. According to Hallanoro, the size is about 5 cubic meters per 100kW, the price is 4000 Euros per kW, the overall efficiency is 60%, and the current density is 0.25 amps per square centimeter (Hallanoro).

After obtaining the specifications of the fuel cells, maximum potential of the cells was calculated to be around 1.2 volts using the Nernst equation. After determining the maximum potential for the cells, resistance and polarization were taken into account using Kabza's formulary to determine the effective cell voltage of 0.98 volts. The number of stacks and required natural gas flow rate were subsequently calculated to be 2038 stacks and around 20 million cubic feet of natural gas per year. The energy production for the fuel cells was found to be 172,000 MWh per year which fulfills the energy requirements for the University.

Solid oxide fuel cells were chosen for their high efficiency and relative cathode and anode sturdiness. In order to maximize efficiency, the fuel is reformed into hydrogen before entering the fuel cells to reduce the degradation of the fuel cell. SOFC's have the ability to utilize hydrocarbons as fuel and therefore eliminate any danger of contaminating the cell.

TE-101-5094 Electric Thermal Element

The Electric Thermal Element is a necessary piece of equipment for start-up. In order for the necessary reactions to occur in the fuel cells, the temperature of the cell must at least be 650 degrees Celsius. All reactions in the fuel cell are exothermic and produce the heat required for the reaction to continue and the thermal element is no longer required once the reaction reaches steady state. Industry standards state that heaters are typically electric and must be located inside of the fuel cells (Batelle Memorial Institute). After searching for the best preheater element online, a paper was found that has the capability to reach the steady state temperature in 3 minutes (Bosel, 2012). Each cell needs a heating element so there is exactly 150 heating elements per stack. With an estimated downtime of only once every two years according to the CEO of Elcogen, the total amount of energy is around 0.23 MWh per year (Hallanoro). This allows the fuel cell to reach its maximum efficiency and produce the heat required for the reaction to continue.

HR-101-2 Organic Rankine Cycle

The organic rankine cycle systems are used to recover waste heat from the streams leaving the fuel cells. The outlet streams also condense water due to the cooling. Because the systems are prepackaged there is no material selection required for the system and all that is required is sizing based on the flowrate of water. The outlet stream from the fuel cells contains 20,000 kg/hr of water, which needs two systems to produce 115kW of energy per system (Products). The ORC systems are purchased from Calnetix Technologies and have little to no maintenance cost because of the closed cooling systems inside the prepackaged units. The system is contained in a 6 meter long storage container with the evaporator, condenser, power delivery unit, power electronics cooler, refrigerant leak detector, air compressor, space heater, exhaust fan, and lights inside (Products). The energy output is added onto the total energy produced by the entire process but is used to negate the energy requirement of the preheater or fan.

V-101 MEA Storage Tank

A storage tank is located on-site for the storage of monoethanolamine, the absorbent used in the CO_2 scrubber. The storage tank is designed to hold enough MEA for a half day supply and has a working volume of 85%. MEA is pumped from the storage tank to the CO_2 scrubber.

P-101 A/B MEA Pump

A centrifugal pump is used to move the MEA absorbent from the storage tank to the absorption column.

T-102-103 Carbon Dioxide Scrubber

A carbon dioxide scrubber is used in this process to reduce and prevent CO_2 emissions into the atmosphere. The CO_2 scrubber is a packed bed absorption column and uses a liquid absorbent, monoethanolamine (MEA) to remove CO_2 from the process stream (Ledjeff-Hey). The packing in the column is composed of three inch ceramic Raschig Rings (Theodore). The CO_2 scrubber operates at ambient temperature and pressure. A CO_2 scrubber is very environmentally beneficial due to its significant reduction of carbon dioxide emissions from the plant.

MEA saturated with CO_2 can be regenerated by contacting the saturated MEA with hot pressurized steam. This plant was designed with two CO_2 scrubbers so that one can be used to regenerate saturated MEA while the other is used to remove CO_2 from the process stream. The CO_2 that is removed from the MEA is then be transported from the plant for use in another industry.

Economic analysis of the process suggests that the design is currently not feasible. However, the driving factors that make the capital and operating costs so high are all related to the CO_2 scrubbing operation. The equipment as well as the absorbent are very expensive and drive up the capital cost and operating costs significantly. If the CO_2 scrubber were removed completely or replaced with a different unit operation to capture CO_2, the plant may be economically feasible. More detailed economic analysis is discussed in section 6.

4. Safety Issues

The plant contains safety equipment necessary for fire prevention. Fire extinguishers, emergency shut off valves, controllers, fire blankets, spark proof outlets and switches are all necessary due to the flammability and explosiveness of methane and hydrogen. No smoking, lighters, or ignition sources are allowed in the plant for fire safety. Workers are trained on methane and hydrogen handling and safety compliance to OSHA standards (OSHA). Gas sensors for methane, carbon dioxide, and carbon monoxide are use in case of leaks in equipment or pipes.

OSHA approved high temperature suits are used around fuel cells due to the high temperatures of up to 700 degrees Celsius. Employees working with fuel cells must wear suits when working with operating fuel cells and trained on startup and shutdown of the plant (OSHA). High temperature suits and training are the special requirements for this plant.

Safety risks with the equipment include fuel cells, steam methane reformer, preheater, ORC system, desulfurizer column.

Fuel Cells: Safety risks are due to high temperatures, electrically issues and flammability. The fuel cells operate at high temperatures, so temperature suits and training are necessary for maintenance. Start up and shutdown procedures are followed because rapid change in temperature can lead to cracking or damage to fuel cells. Fuel cell temperatures are monitored at all times and safety assessments are conducted monthly. Flammability of hydrogen and natural gas is a high concern and can lead to explosions. The fuel cells are producing energy at a constant rate year-round, so electrical hazards are considered. Proper training with high voltage and currents is necessary for electrocution hazards.

Steam methane reformer: Main considerations are for temperature and flammability control. Methane reactions can lead to explosions or runway reactions and are monitored, and equipment safety checks are necessary for all pipes and reformer. High pressures with combustible gases can lead to explosions. Pressures are monitored at all times as this can also affect the production of hydrogen.

Preheater: Safety considerations for temperature are taken. Air is 700 degrees leaving the preheater which can lead to burns and fire. Combustible materials and debris must be away from the preheater and maintenance for pipes and walls are done if necessary.

ORC: Cools steam and gas from high temperatures so cooling is monitored. Buildup of gas can lead to high pressures which can damage equipment. This can cause hazards in the carbon dioxide scrubber and piping surrounding the system.

Desulfurizer Column: Considerations are for temperature, pressure, and adsorbent. High temperatures can ignite natural gas with presence of air and high pressures can lead to column bursting. Reaction kinetics and flow is checked because lack of sulfur removal poisons the fuel cells and lead to damage throughout the process. Adsorbents are replaced to ensure sulfur removal is happening. After the sulfur is removed from natural gas a hazard is created because gas does not smell if there is a leak. This hazard is accounted for with methane sensors and carbon monoxide sensors.

All equipment hazard summaries refer to the individual HAZOPs attached in the appendices.

Chemical safety considerations are necessary for hydrogen, natural gas, air, and MEA storage. Hydrogen and natural gas are operated in separation from air (oxygen) unless in specific operating equipment. Natural gas and hydrogen ignite with high temperatures and in the presence of air. Piping and transportation are separate from each other and comply to OSHA regulations for hydrogen and natural gas (OSHA). Line cross over or damaged pipes need to be removed to prevent any ignition of these gases. MEA needs tank storage as described in the equipment description separate from the carbon dioxide scrubber. The storage tank can contain a half day supply, so it can be separate from the system.

5. Environmental Impact Statement

One of the highlights of using fuel cells as an energy source is the reduced impact on the environment. Fuel cells are known to be very sustainable and environmentally friendly. According to the University of Arizona's energy manager, Michael Hoffman, 67-70% of the energy used by the campus is purchased from TEP and the rest is produced mostly by on-campus turbines (Hoffman). TEP generates their energy through a mixture of coal and natural gas power plants ("TEP Analyzing Impact…"). Overall, this fuel cell facility would not only help create green energy, but it would also allow the University of Arizona to become independent from TEP and go "off-the-grid".

The designed process utilizes natural gas as a fuel source. This fuel source is used in order to reduce the degradation of the cathode and anode of the fuel cell. Typically, power plants utilize coal and natural gas as fuel sources. TEP currently produces 69% of their power through coal-fired power plants according to TEP's 2017 Integrated Resource report (TEP). Coal is considered one of the most environmentally damaging sources of energy. Coal-fired power plants emit chemicals such as carbon dioxide, sulfur dioxide, nitrogen oxide, and mercury into the air. Typically, some of the ash is caught, recycled, and repurposed but a large majority is put into long term storage. Chemicals such as selenium, lead, cadmium, arsenic, mercury, thallium, and chromium are stored under water for the long term ("Coal Combustion Wastes"). This storage often leads to the leaching of these chemicals into the water streams and throughout the natural environment. The designed fuel cell process would not produce any of the toxic chemicals listed and would improve upon overall air quality and decrease environmental toxicity.

Leaks are one of the major concerns when using natural gas as a fuel source. The concern is increased after the desulfurizer because hydrogen sulfide gives natural gas its smell. Without the smell of sulfur, it is much harder to detect leaks. A natural gas leak would have a major impact on environment with regards to our global warming effect. The global warming potential of methane is 21 times greater than that of carbon dioxide and drastically increases the negative effects on the atmosphere.

A fence-to-fence life cycle assessment on the facility was performed and the results can be seen in Figure 3 below. Three major sections were analyzed in the LCA: Atmospheric Environment, Human Health, and Natural Resources. The atmospheric environmental impact is calculated below from the amount of carbon dioxide produced in the process. Human health effects are very minimal due to the safe products of carbon dioxide and water vapor. One of the major highlights of using the fuel cell process is the mitigation of heavy metal use for energy production and the reduction of their negative health effects. Due to the relatively small size of fuel cells, the facility does not need large amounts of land. Natural gas and water consumption is an important factor in natural resources.

The only products created by the fuel cell process are water vapor and carbon dioxide. According to TEP, 1,562 lbs of carbon dioxide are produced for every MWh of electricity ("TEP Analyzing Impact…"). According to the environmental calculations, TEP currently produces 123 million kilograms of carbon dioxide per year to generate the 173,000 MWh that the proposed fuel cell facility would produce (Appendix A). Without a carbon dioxide scrubber, the proposed fuel cell facility would generate 105 million kilograms per year (Appendix A). With the carbon dioxide scrubber installed, the facility reduces the carbon dioxide produced to around 3.2 million kg of carbon dioxide (Appendix A). The carbon dioxide captured through the scrubber is then given to Kalil Bottling Company for their Monster Energy plant in Phoenix ("Monster Energy"). The transportation of the carbon dioxide is Kalil's responsibility in return for a free source of carbon dioxide.

There are few utilities needed to run the facility. The facility essentially powers itself through its electricity production. One of the major utilities needed is the steam for the reforming step. While the fence-to-fence LCA does not require the calculation of carbon dioxide produced by the creation of steam being used in the process, this report notes that steam creation accounts for large sources of carbon dioxide emission outside of the facility. According to the State of Oregon Department of Environmental Quality, 94.67 kilograms of carbon dioxide for every mmBtu of steam produced ("Greenhouse Gas"). Using this information, a calculation of the carbon dioxide produced yielded 21 million kilograms per year. Cooling water is used at rate of 2000 liters per hour but can be recycled through the University and therefore has a negligible environmental effect.

Overall, the environmental effects this facility would produce are small compared to current power plant energy production. One of the largest incentives in building this facility would be the decreased environmental impact and reduced reliance on coal-fired power plants.

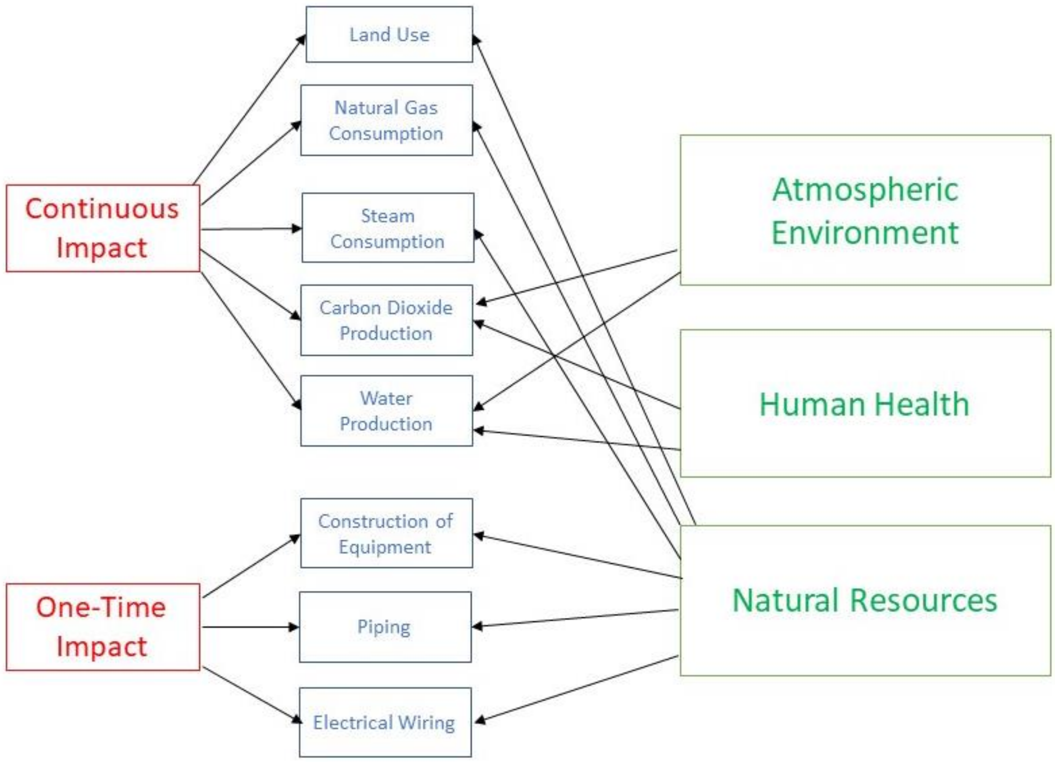

Figure 3. Components of Life Cycle Assessment

6. Economic Analysis

The equipment and capital costs were calculated using steps and equations from chapters 16 and 17 of *Product and Process Design Principles* (Seider). The bare module costs of all the equipment are in table IV and the total bare module cost of the equipment for this plant is \$95 million. The piece of equipment with the largest bare module cost is the carbon dioxide scrubber, which costs \$88 million for two scrubbing columns. To significantly reduce the equipment cost as well as the operating costs of the plant, the CO_2 scrubber could be removed.

Currently, the carbon dioxide scrubber is included in the process because it significantly reduces the pollution and environmental footprint of the plant by capturing waste CO_2 instead of releasing it to the atmosphere. However, different, more economical methods for CO_2 capture could be considered to replace the carbon dioxide scrubber, while still maintaining low levels of CO_2 released to the atmosphere. In analyzing the equipment costs it can be seen that the calculated bare module cost of the CO_2 scrubber is \$88 million and the total bare module cost of the equipment is calculated to be $95 million. Reducing the cost of the unit operation for CO_2 removal would make the plant more economically feasible.

Table IV. Bare Module Cost of Equipment

Equipment	**Bare Module Cost, C_{BM}**
Desulfurizer	$55,000
CO2 Scrubber	$88,000,000
Absorbent Pump	$60,000
Storage Tank	$154,000
Fuel Cell	$5,750,000
SMR	$1,150,000
Preheater	$55,000
Fan	$1,700
ORC	$230,000
Total	$95,500,000

The components of the total capital investment are shown in table V. The total capital investment is $165 million with the largest component being the bare module equipment cost at $95.5 million to pay for all the pieces of equipment needed to run the plant. The components of the total annual production cost are shown in table VI. The total annual production cost is $27.7 million. The total annual cost of feedstocks is $1.13 million which consists of the cost of natural gas, absorbent, and adsorbent. The annual utility cost is $1.14 million consisting mainly of steam and a small part of cooling water. The plant provides its own electricity subtracted from its total production so none needs to be purchased. There is no cost associated with waste disposal as the waste steam is blown into the atmosphere and the waste sulfur and carbon dioxide are stored after being removed from the process. The labor related operations costs were calculated for three operators per shift. The annual cost of manufacture is $27.1 million. Research was not included in the general expenses as the plant only produces power and doesn't conduct any research on its own outside of the University of Arizona.

Table V. Total Capital Investment, C_{TCI}

Components of Total Capital Investment		
Bare module equipment cost	C_{tbm}	$95,500,000
Cost of site preparation	C_{site}	$3,800,000
Cost of facilities	C_{serv}	$4,800,000
Allocated costs	C_{alloc}	$3,000,000
Total Direct Permanent Investment	C_{dpi}	$107,000,000
Contingencies and contractors	C_{cont}	$19,000,000
Total Depreciable Capital	C_{tdc}	$126,000,000
Cost of land	C_{land}	$2,500,000
Cost of royalties	C_{royal}	$2,500,000
Cost of startup	$C_{startup}$	$12,600,000
Total permanent investment	C_{tpi}	$144,000,000
Working capital	C_{wc}	$21,600,000
Total Capital Investment	C_{tci}	$166,000,000

Table VI. Annual Operating Costs

Cost Factor	**Annual Cost ($/yr)**
Feedstocks (raw materials)	$1,100,000
Utilities	
Electricity	$134,000
Steam	$1,100,000
Cooling water	$200
Refrigerant	$0
Waste disposal	$0
Operations (labor-related) (O)	
Direct wages and benefits (DW&B)	$1,000,000
Direct salaries and benefits	$160,000
Operating supplies and services	$63,000
Technical assistance to manufacturing	$180,000
Control laboratory	$260,000
Maintenance (M)	
Wages and benefits (MW&B)	$4,400,000
Salaries and benefits	$1,100,000
Materials and services	$4,400,000

Maintenance overhead	$220,000
Operating overhead	
General plant overhead	$478,000
Mechanical department services	$161,000
Employee relations department	$397,000
Business services	$498,000
Property taxes and insurance	$2,500,000
Depreciation	
Allocated plant	$8,900,000
Cost of Manufacture (COM)	$27,200,000
General expenses	
Selling (or transfer) expense	$147,000
Direct research	
Allocated research	
Administrative expense	$294,000
Management incentive compensation	$184,000
Total General Expenses (GE)	$625,000
Total Annual Production (C)	$27,900,000

Table VII. shows the cash flow and net present value (NPV) calculations for the plant, indicating that the plant as it is currently designed is not economically feasible. MACRS straight line, ten year depreciation method was used for the NPV table. The NPV of the plant is never positive, therefore it would be necessary to modify the current design before constructing the plant.

Table VII. NPV Table

	Total Depreciable Capital Investment	Working Capital	Depreciation (MACRS 10yr straight line)	Annual Cost (COM) excluding depreciation	Annual Sales			
Year	fC_{TDC}	C_{WC}	D	COM-D	S	Net earn	Cash flow, C	Cum PV @ 15%
0	$(42,000,000)						$(42,000,000)	
1	$(42,000,000)						$(42,000,000)	$ (36,500,000)
2	$(42,000,000)	$(21,600,000)					$(63,600,000)	$ (84,700,000)
3			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (82,000,000)
4			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (80,000,000)
5			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (77,800,000)
6			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (76,000,000)
7			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (74,600,000)
8			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (73,200,000)
9			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (72,100,000)
10			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (71,200,000)
11			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (70,300,000)
12			$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 4,000,000	$ (69,500,000)
13		$21,600,000	$ 16,500,000	$ 10,700,000	$ 14,700,000	$ (12,600,000)	$ 25,500,000	$ (65,400,000)

Due to the high bare module cost and operating costs of the plant, it is not economically feasible. The annual spending by the university is currently $12.9 million, and the calculated annual operating cost for this plant is $27.8 million. Since the proposed operating costs are higher than current costs, there is no payback period and no positive return on investment.

One economic hazard for the plant would be an increase in natural gas prices. Natural gas is necessary for the reaction in the fuel cells that generates electricity, so operating costs would increase accordingly if natural gas prices increased. Another economic hazard is the fuel cells, which are the second largest equipment cost for this plant. They are sensitive to certain chemicals such as sulfur, which poison the catalyst in the fuel cells. The fuel cells also require precise thermal management. If there are deviations from ideal operating conditions or if chemicals such as sulfur come in contact with the fuel cells, they deteriorate rapidly requiring the fuel cells to be replaced more frequently, which would be a large expense.

7. Conclusions and Recommendations

While fuel cells are a cleaner energy source than how TEP generates its electricity, the annual cost of the plant far exceeds the current amount the University pays for electricity making the plant unfeasible to build. In order for the plant to be feasible without the University having to pay more the overall cost of the plant needs to be reduced. One way to do this to remove the carbon dioxide scrubber from the process as it is the highest equipment cost and the absorbent it uses is the second highest utility cost. Removing the carbon dioxide scrubber does make the plant feasible however it is harmful for the environment. It was decided that for this project that the harm to the environment outweighed the economic benefit to the University. The plant may be feasible in the future if technological advances reduce the cost of the equipment or the feedstocks or if the efficiency of the steam methane reformer or fuel cells is increased.

8. References

Al-Hamamre, Zayed. "Fuel Cell Principle: Electrochemistry & Reaction Kinetics." Special Topics (Fuel Cell Fundamentals and Technology). file:///C:/Users/ryand/Downloads/Lecture%204-Fuel%20Cell-Electrochemistry%20and%20Reaction%20Kinetics.pdf.

Basye, L., and S. Swaminathan. "Hydrogen Production Costs -- A Survey." Apr. 1997, doi:10.2172/674693.

"BAN THAI TRADING CO.,LTD,Thailand." Www.buyimporter.com, www.buyimporter.com/1006/?id=ban-thai-trading-co-ltd.

Bhatia, M. V. 1977. Packed tower and absorption design. In P. N. Cheremisinoff and R. A.Young (Eds.),Air Pollution Control and Design Handbook. New York: Marcel Dekker.

Bossel, Ulf. "Rapid Startup SOFC Modules." Energy Procedia, Elsevier, 30 Sept. 2012, www.sciencedirect.com/science/article/pii/S1876610212013951.

"Coal Combustion Wastes." Ground Truth Trekking, www.groundtruthtrekking.org/Issues/AlaskaCoal/Coal-Ash-Combustion-Wastes.html.

"Colleges Are Counting on Clean Energy from Fuel Cells to Go Green." *University Business Magazine*, UB Custom Publishing, 24 Nov. 2015, www.universitybusiness.com/article/colleges-are-counting-clean-energy-fuel-cells-go-green.

Crowe, Robert. "Capturing Waste Heat with Organic Rankine Cycle Systems." Renewable Energy World, 24 Jan. 2011, www.renewableenergyworld.com/articles/2011/01/capturing-waste-heat-with-organic-rankine-cycle-systems.html.

DME Catalog. DME, 2014, na.dmecompany.com/Catalog/CatalogListing.aspx?CatalogId=DME&CatalogDetailId=1705.

“Economic Indicators.” Chemical Engineering Science, June 2017, www.chemengonline.com/.

“Electricity in the United States.” *Electricity in the United States - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration*, www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states.

Fu, Dong, LiHong Chen, and LiGuang Qin. "Experiment and model for the viscosity of carbonated MDEA–MEA aqueous solutions." Fluid Phase Equilibria 319 (2012): 42-47.

“Fuel Cells.” Concordia University , users.encs.concordia.ca/~pillay/fuel-cells.html.

“Fuel Cells.” *Energy.gov*, www.energy.gov/eere/fuelcells/fuel-cells.

“FuelCellToday - The Leading Authority on Fuel Cells.” Fuel Cell Applications - Fuel Cell Today, www.fuelcelltoday.com/applications.

“Greenhouse Gas Steam Calculator - Oregon.gov.” State of Oregon Department of Environmental Quality.

Guangda, ZHAO, et al. “Natural Gas Transmission Pipeline Temperature Drop Calculation.” *CSCanada*, vol. 7, no. 2, Nov. 2014, pp. 127–131., doi:10.3403/30055564.

Hagewiesche, Daniel P., et al. "Absorption of carbon dioxide into aqueous blends of monoethanolamine and N-methyldiethanolamine." Chemical Engineering Science 50.7 (1995): 1071-1079.

Hallanoro, Paul. “University of Arizona Energy Production.” University of Arizona Energy Production, 26 Mar. 2018.

Hoffman, Michael. “Energy Usage of the University of Arizona - Engineering Senior Design Project.” Energy Usage of the University of Arizona - Engineering Senior Design Project, 25 Jan. 2018.

Institute, Battelle Memorial. “Manufacturing Cost Analysis of 100 and 250 KW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications.” *energy.gov*, Jan. 2016, https://www.energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf

Kabza, Alexander. "Fuel Cell Formulary." www.pemfc.de/FCF_Smart.pdf.

Ledjeff-Hey, K., J. Roes, and R. Wolters. "CO2-scrubbing and methanation as purification system for PEFC." *Journal of Power Sources* 86.1-2 (2000): 556-561

"Monster Energy | Arizona | Kalil Bottling Co." Monster Energy | Arizona | Kalil Bottling Co, www.kalilbottling.com/.

Natural Zeolites & Synthetic Zeolites, Reade International Corp, www.reade.com/products/natural-zeolites-synthetic-zeolites.

"NIST Chemistry WebBook, SRD 69." *NIST Chemistry WebBook*, webbook.nist.gov/chemistry/.

OSHA. "Heat Stress: OSHA Regulations." *Findlaw*, smallbusiness.findlaw.com/employment-law-and-human-resources/heat-stress-osha-regulations.html.

OSHA. "UNITED STATES DEPARTMENT OF LABOR." *Occupational Safety and Health Administration*, www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9749.

"Products | ACCESS ENERGY® THERMAPOWER® ORC." *Access Energy Thermapower Specifications | Calnetix*, www.calnetix.com/access-energy-thermapower-specifications.

Rochelle, Gary T. "Amine scrubbing for CO2 capture." Science 325.5948 (2009): 1652-1654.

Seider, Warren D. Product And Process Design Principles : Synthesis, Analysis, and Evaluation. New York :Wiley, 2004. Print.

"TEP Analyzing Impact Of New Carbon Dioxide Emission Limits For Power Plants." Tucson Electric Power, www.tep.com/news/tep-analyzing-impact-of-new-carbon-dioxide-emission-limits-for-power-plants/.

TEP. "TEP-2017-Integrated-Resource."

Theodore, Louis, and Francesco Ricci. Mass Transfer Operations for the Practicing Engineer. Wiley, 2010.

"U Of A CHEE Senior Design Project." Received by Rosemary Cox-Galhotra, U Of A CHEE Senior Design Project, 19 Mar. 2018.

Wappel, D., et al. "Ionic liquids for post-combustion CO2 absorption." International Journal of Greenhouse Gas Control 4.3 (2010): 486-494.

Yang, Ralph T., Arturo J. Hernández-Maldonado, and Frances H. Yang. "Desulfurization of transportation fuels with zeolites under ambient conditions." Science 301.5629 (2003): 79-81.

Xu, Jianguo, and Gilbert F. Froment. "Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics." AIChE journal 35.1 (1989): 88-96.

Appendix A- Final Calculations

Desulfurization Adsorption Calculations

$$t_{cycle} = t_{ads} * 2$$

$$Mass\ S\ adsorbed\ during\ 1\ cycle = mole\ flow\ rate\ S * t_{ads} * fraction\ S\ removed * MW\ S$$

$$Adsorbent\ mass\ required\ for\ 1\ cycle = Adsorbent\ working\ capacity * Amount\ of\ sulfur\ adsorbed$$

$$Adsorbent\ bed\ volume = \frac{Adsorbent\ mass}{Adsorbent\ bulk\ density}$$

$$Face\ area\ of\ bed = \frac{Gas\ volumetric\ flow\ rate}{Gas\ velocity}$$

$$Radius\ of\ Column = \sqrt{\frac{Face\ area\ of\ bed}{pi}}$$

$$Bed\ length = \frac{Bed\ volume}{Bed\ face\ area}$$

Steam Methane Reformer Calculations

$$\frac{1{,}206{,}236\ mol\ H_2}{1\ hr} * \frac{1\ g\ H_2}{1\ mol\ H_2} * \frac{1kg}{1000\ g} * \frac{11.126\ Nm^3\ H_2}{1\ kg\ H_2} * \frac{24\ hr}{1\ day} = \frac{322{,}094\ Nm^3 of\ H_2}{day}$$

$$Cost\ of\ SMR = \$1.03 * 10^6 * \left(Plant\ Capacity\ in\ million \frac{Nm^3}{day}\right)^{0.3}$$

$$\frac{322{,}094\ Nm^3\ H_2}{day} \div 1{,}000{,}000 = 0.3221 \frac{million\ Nm^3}{day}$$

$$Cost\ of\ SMR = \$1.03 * 10^6 * (0.3221)^{0.3} = \$733{,}216$$

$$PV = nRT$$

$$V = \frac{2{,}135{,}028\ mols\ (0.08314 \frac{L * bar}{mol * K})(700 + 273.15)}{3\ bar} = 57.6\ million\ L$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

$$701{,}300\ mol\ CH_4 * 0.57\ reaction\ conversion = 399{,}741\ mol\ CH_4\ reacted$$

$$2 * 399.741\ mol\ of\ CH_4 = 799{,}482\ mol\ of\ H_2O$$

$$399{,}741\ mol\ CH_4 = 399{,}741\ mol\ CO_2$$

$$4 * (701{,}300 - 399{,}741\ mol\ CH_4) = 1{,}206{,}236\ mol\ H_2$$

CO_2 Scrubber Calculations

Overall Mole Balance: $G_1 + L_2 = G_2 + L_1$

Component Mole Balance: $G_1 y_1 + L_2 x_2 = G_2 y_2 + L_1 x_1$

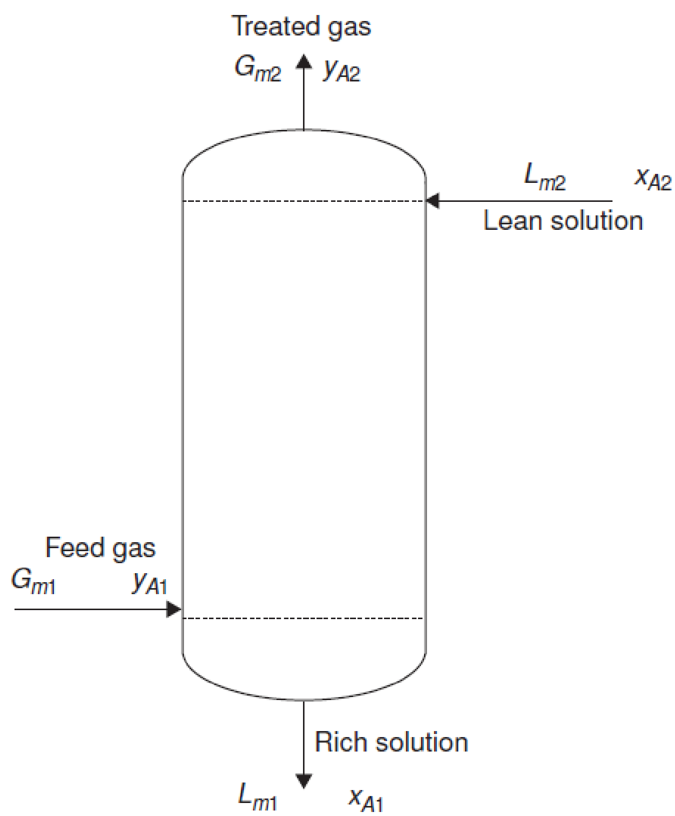

Figure 10.7 Mole balance; countercurrent flow.

Given/Know: G, y_1, y_2, x_1, x_2

$$L_{min} = \frac{y_1 - y_2}{x_1 - x_2} * G$$

$$L_{act} = 1.5 * L_{min}$$

Calculating Column Dimensions (following steps outlined in *Mass Transfer Operations for the Practicing Engineer*)

1. Abscissa/ x-coordinate (α) to use Figure 10.11 (see figure below)

$$\alpha = \left(\frac{L}{G}\right)_{act} * \left(\frac{\rho_G}{\rho_L}\right)^{\frac{1}{2}}$$

2. Read y-coordinate (β) at flooding line from Figure 10.11 (see figure below)

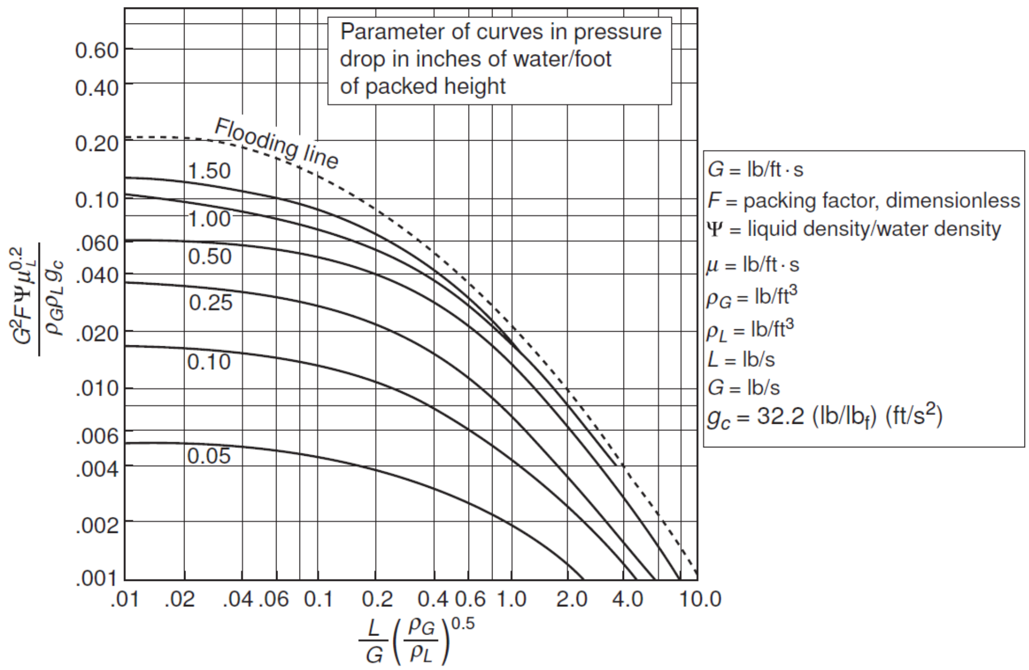

Figure 10.11 Generalized pressure drop correlation to estimate column diameter.

Theodore, Louis, and Francesco Ricci. Mass Transfer Operations for the Practicing Engineer. Wiley, 2010.

$$G_f = \left(\frac{\beta * \rho_G * \rho_L}{F * {\mu_L}^{0.2}}\right)^{\frac{1}{2}}$$

$$Cross\ Sectional\ Area\ (S) = \frac{Gas\ mass\ flow}{fraction\ of\ flooding\ velocity * G_f}$$

$$Column\ Diameter\ (D) = 2 * \left(\frac{Cross\ Sectional\ Area}{\pi}\right)^{\frac{1}{2}}$$

$$Column\ Height\ (Z) = H_{og} * N_{og}$$

$$N_{og} = \ln\frac{y_1}{y_2}$$

H_{og} is the height of a single packing unit. For these calculations, a value was assumed based on examples from literature.

N_{og} is the number of overall transfer units.

Appendix B- Overall Mass Balance

Table I. Component Mass Balance

Stream	H_2 (kg/hr)	CH_4 (kg/hr)	O_2 (kg/hr)	H_2O (kg/hr)	CO_2 (kg/hr)	N_2 (kg/hr)	H_2S (kg/hr)	MEA (kg/hr)	Total (kg/hr)
1	0	4383	0	0	0	126	0.000326	0	4509
2	0	0	0	0	0	0	0.000326	0	0
3	0	4383	0	0	0	126	0	0	4509
4	0	0	0	9847	0	0	0	0	9847
5	1262	1885	0	4234	6854	126	0	0	14361
6	0	0	99667	0	0	328247	0	0	427914
7	0	0	82181	19693	12025	328373	0	0	442272
8	0	0	0	19693	0	0	0	0	19693
9	0	0	82181	0	12025	328373	0	0	422579
10	0	0	0	0	0	0	0	68414	68414
11	0	0	82181	0	361	328373	0	0	410915
12	0	0	0	0	11664	0	0	68414	80078

Table II. Overall Mass Balance

In (kg)	Out (kg)	Difference	% Difference
510683	510686	2.47	0.00048

Statement of Roles and Responsibilities

Ashley McDaniel performed the design and economic calculations for the desulfurization column, the carbon dioxide scrubber, and the pump using literature values and textbook resources. She also did the overall economic analysis, calculating the bare module cost of the equipment, the total capital investment, the annual operating cost, and the net present value table. Ashley wrote the sections about these pieces of equipment and the economic analysis section of the report. Additionally, she contributed to the current market information section and she wrote the written description of the process.

James Charron designed the steam methane reformer. He researched existing process and applied those concepts and literature values in performing his own design calculations as well as the calculations for the equipment and operating costs related to the steam methane reformer. Additionally, James tracked the utilities needed for each unit operation and performed the necessary calculations. James contributed the sections about the steam methane reformer and utilities as well as a portion of the economic analysis section and the conclusion of the report.

Ryan Dunham designed the fuel cell system and electronic heating elements by contacting vendors and using values from literature. He was responsible for the design calculations for the fuel cell system as well as the economic analysis for the fuel cells. He also analyzed the environmental implications of the entire plant. Ryan wrote the sections of the report about the fuel cells and the environmental analysis. Additionally, he wrote the rationale for the process choice. He helped create the block flow and process flow diagrams.

James Hattel was responsible for the design of the Organic Rankine Cycle, fan, and preheater. He completed the design calculations using information from vendors as well as literature values. James also did the economic calculations for these pieces of equipment. He wrote the sections of the report about these pieces of equipment. Additionally, he contributed to the section for current market information and he summarized everyone's safety analysis of a specific unit operation and wrote the safety section of the report. James drew the block flow diagram and the process flow diagram.